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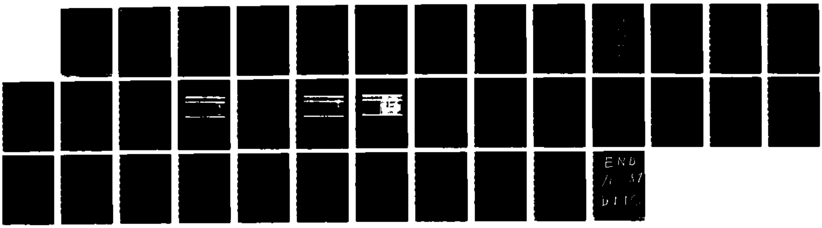

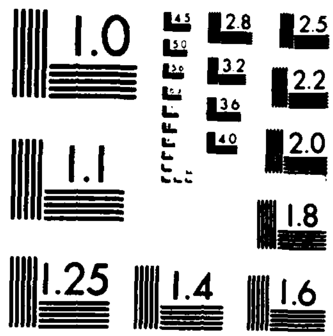

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A SINGLE-STATION WEATHER FORECASTING EXPERT SYSTEM

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AIR FORCE GEOPHYSICS LABORATORY
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This report describes the development of an early prototype expert system for the classical single-station weather forecasting problem. The skills required to maximize forecast quality based on such limited data are being lost though they continue to have application to certain military scenarios which include communications interruptions. Knowledge for the expert system was obtained from a meteorologist experienced in single-station weather forecasting by working through case study data. The prototype was developed on a micro-computer and uses forward and backward chaining rules, frames, and other functions and procedures written in LISP. The expert system is able to emulate the expert for a several day case study used in the development, although much more work must be done to make the system useful for the general meteorological situation.

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TABLE OF CONTENTS

1. INTRODUCTION

The needs of the Armed Services for accurate, timely forecasts of environmental conditions have become increasingly critical with the evolution of current operational requirements and sophisticated weapons systems. Accurate forecasts of basic meteorological fields such as wind, temperature, cloud cover, precipitation, and visibility are essential for the planning and execution of successful operations.

Objective techniques for preparing these forecasts include sophisticated numerical weather prediction models and statistical models. Numerical weather prediction models require extensive sets of observations for their initialization and execute on large mainframe computers. Because of the time required to gather and process the observations, run a model, and post-process the model output, most operational numerical models have their greatest utility for forecast times of 12 hours and longer. This fact is emphasized by the models' inability to handle small-scale or rapidly changing meteorological conditions that can profoundly impact local weather. Statistical models are useful for short range weather forecasting, but their application usually depends on long term data records which vary from place to place. Skilled and experienced meteorologists are perhaps the best solution to the short term weather forecast problem, but they are in short supply.

Artificial Intelligence (AI) has long been recognized as a potentially powerful tool for solving difficult problems of this nature, and a subclass of this field, expert systems, has been developed to encapsulate the knowledge of an expert and make it useful to less experienced individuals.

During the past two years, several meteorological expert systems have been developed. The applications range from forecasting snowfall in Colorado (Swetnam and Dombroski[1]), to forecasting of severe weather (Riese and Zubrick;[2] Elio, de Hann and Strong[3]), to interpretation of radar imagery in detecting microbursts and gust fronts (Campbell;[4] Olson[5]). Though all of these systems are experimental, some of these systems are being evaluated in the field.

This report describes the development of an expert system for the classical single-station forecasting problem. Specifically, the system is being designed to provide a short-range (0-6 hour) forecast utilizing only surface and upper air data observed at a mid-latitude station. The methods used in single-station forecasting date back many years and are best described in the classic article by Oliver and Oliver.[6]

The development of an expert system to deal with this particular forecasting problem is important for several reasons. First, even though the single-station forecasting

methodology has existed for some time, the problem is relevant to modern military scenarios involving remote locations that may encounter communications interruptions and/or a lack of experienced forecasters. Second, an expert system addressing this problem could improve local short-range forecasts by providing the meteorologist with expertise that may not be commonly used. Third, this system would be a logical starting point for a much more complex expert system that could assimilate input from a variety of sources such as numerical models, radar, satellites, etc., and combine and interpret the data with a result similar to that of an expert synoptician operating in an environment free of time constraints. Finally, single-station forecasting is the kind of problem for which expert system methodology can provide benefit over traditional problem solving techniques. It is a classical case of inferencing from incomplete or sparse data, a difficulty the human mind is often able to overcome with an ease unknown to digital processing machines.

The expert system described in this report is an early prototype or proof-of-concept system which is designed to emulate the process by which the expert makes a forecast. Because of this, there was no constructive reason for objective verification studies at this time, and none were performed. Qualitatively, results between the single-station expert system and the expert were very similar. The knowledge currently incorporated into this system is the result of a four-day case study analyzed extensively by an expert. The rules and functions that describe this knowledge do not cover the rich variety of meteorological events or phenomena commonly observed, even at a given station. However, the structure developed for this expert system is a general one in which the knowledge base can be substantially expanded to encompass the general short-range forecast problem for an arbitrary station.

This report is divided into three sections which include a brief description of the knowledge acquisition process, followed by a description of the expert system and a discussion of the knowledge representation. It is not intended to present a complete and thorough discussion of expert systems or their terminology. [Sources of background information about expert systems include Harmon and King[7] and Waterman[8].]

2. KNOWLEDGE ACQUISITION

Knowledge acquisition is the process of obtaining the expertise of an expert. This is not a straightforward process, primarily because experts seldom describe their solution to a problem in a way that accurately reflects their problem-solving process. True expert problem solving is more an intuitive process rather than a rigorously defined sequence

of steps. Experts may easily verbalize the major steps in their decision-making process and pass over without comment the many intermediate, but necessary, supporting facts that went into their final conclusion. The nature of expertise and the methods of obtaining it in useful forms from experts has been studied extensively by psychologists and others. A detailed description of the problem and the process of knowledge acquisition may be found in most books on expert systems (e.g. Waterman[8]).

The expert used in the development of this system is Prof. Walter K. Henry, a former professor at Texas A&M University. Prof. Henry has had extensive experience in single-station forecasting, both as a practitioner and teacher in the U. S. Air Force and as a university professor teaching synoptic meteorology.

The knowledge acquisition process used in this project changed over time, both as a rapport was established with the expert and as the type of knowledge being sought evolved. Knowledge was obtained primarily through the interview process, in which a case study involving archived meteorological data from a single station was used. In all, the expert was used in four one-week sessions.

During the first one-week session, the expert was given case data consisting of hourly station reports and was encouraged to talk as much as possible as he was evaluating the data, developing a synoptic picture and making a series of short-range (1-12 hour) forecasts. The session was video and audio taped for later review and partial transcription. The process was interrupted only occasionally to prompt the expert to be more descriptive. The first session provided a very good demonstration of the thought processes and framework used by the expert as well as the computations required to diagnose the synoptic situation and provide the forecasts.

The second session was similar to the first except that the expert was questioned more throughout his decision-making process. Though this type of interviewing technique is sometimes discouraged when building expert systems, the personality of the expert contributed to make this method effective in gathering useful information. It was also important in this process that the interviewers were meteorologists and were therefore familiar with the terminology, many of the meteorological techniques and the difficulties of forecasting certain situations. The fact that the dialog was between meteorologists led to several in-depth discussions.

The third and fourth sessions were more a potpourri of activities. The expert evaluated an interactive sounding analysis graphics package that had been developed after the first visit to help him in his analyses, reviewed and

evaluated earlier case studies, discussed a variety of other forecasting problems and situations, and, during the final session, reviewed and suggested rules that were or could be used by the system.

3. EXPERT SYSTEM DESCRIPTION

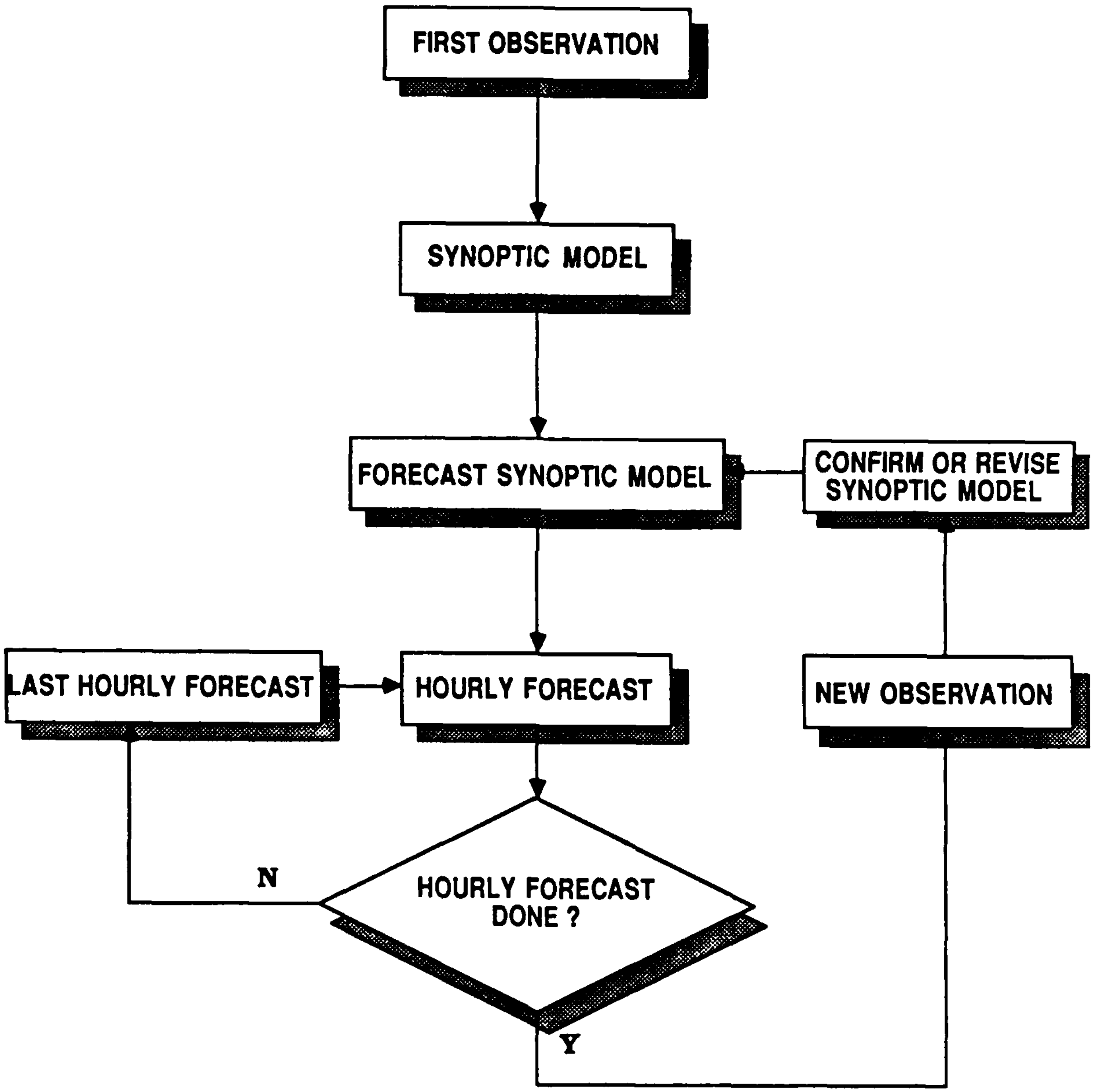
The single-station weather forecasting problem involves a complex combination of physical laws, mathematical computations, derivations and human interpretation, and the development strategy was to imitate the process used by the human forecaster as closely as possible. This required the expert system to have a sophisticated synoptic model representation as well as a computational capability underlying the basic expertise contained in the rules. ES, an EMYCIN-type, rule-based expert system shell developed and used internally by Control Data, was used in this effort because of its flexibility in allowing these features and alternate knowledge representations to be built-in or easily modified. For example, functions were used to represent numerical computations, a frame-based representation was used to describe the synoptic weather model, the hourly observations and the hourly forecasts, and rules were used to implement knowledge of a more empirical nature. Development of the expert system was initiated on a Zenith 100 microcomputer and then migrated to a Zenith 248 microcomputer as the expert system grew. The power of ES allowed the expert system to go beyond the pure rule-based representation to which many microcomputer-based expert systems are limited.

The meteorological forecasting process that is imitated begins with the assimilation of all the pertinent data into a diagnostic model. At the conclusion of this assimilation the meteorologist has a mental model of the current synoptic situation. This is perhaps the most important part of the forecasting process because without a good understanding of the synoptic structure, the forecast is likely to be deficient. The meteorologist then uses this model to project a consistent forecast of future meteorological events.

The forecasting process can be best illustrated in the form of a general flow chart presented in Fig. 1. This figure illustrates the two step process described above. The first is the diagnostic or interpretive task in which the synoptic situation is inferred from the observations, and the second is the forecasting task in which the forecast is inferred from the observations and synoptic situation developed in the first part.

The advantages of structuring the expert system in this two-step formulation are numerous. One of the most important

Fig. 1: FORECASTING PROCEDURE



advantages is that the problem is defined so as to be consistent with the way in which an expert solves the problem. The forecasting expert develops the most complete picture of the synoptic situation before a forecast is even considered. The focus of the forecast is then centered on the synoptic situation with specific modifications made in light of the actual observations. This separation makes it easier to obtain the expert's knowledge appropriate to the particular part of the problem under consideration.

Another related advantage is that rules can be developed independently between the two parts of the problem. This is important because the type of rules or logic used in the two parts is inherently different. The diagnostic or interpretive part must use knowledge in a cumulative sense. Evidence is accumulated as more data become available. The forecasting part must explicitly take time into account in making the forecast. As described in more detail in the forecasting section, the manner in which the problem is structured allows time to be taken into account in a very natural and general way in the forecast.

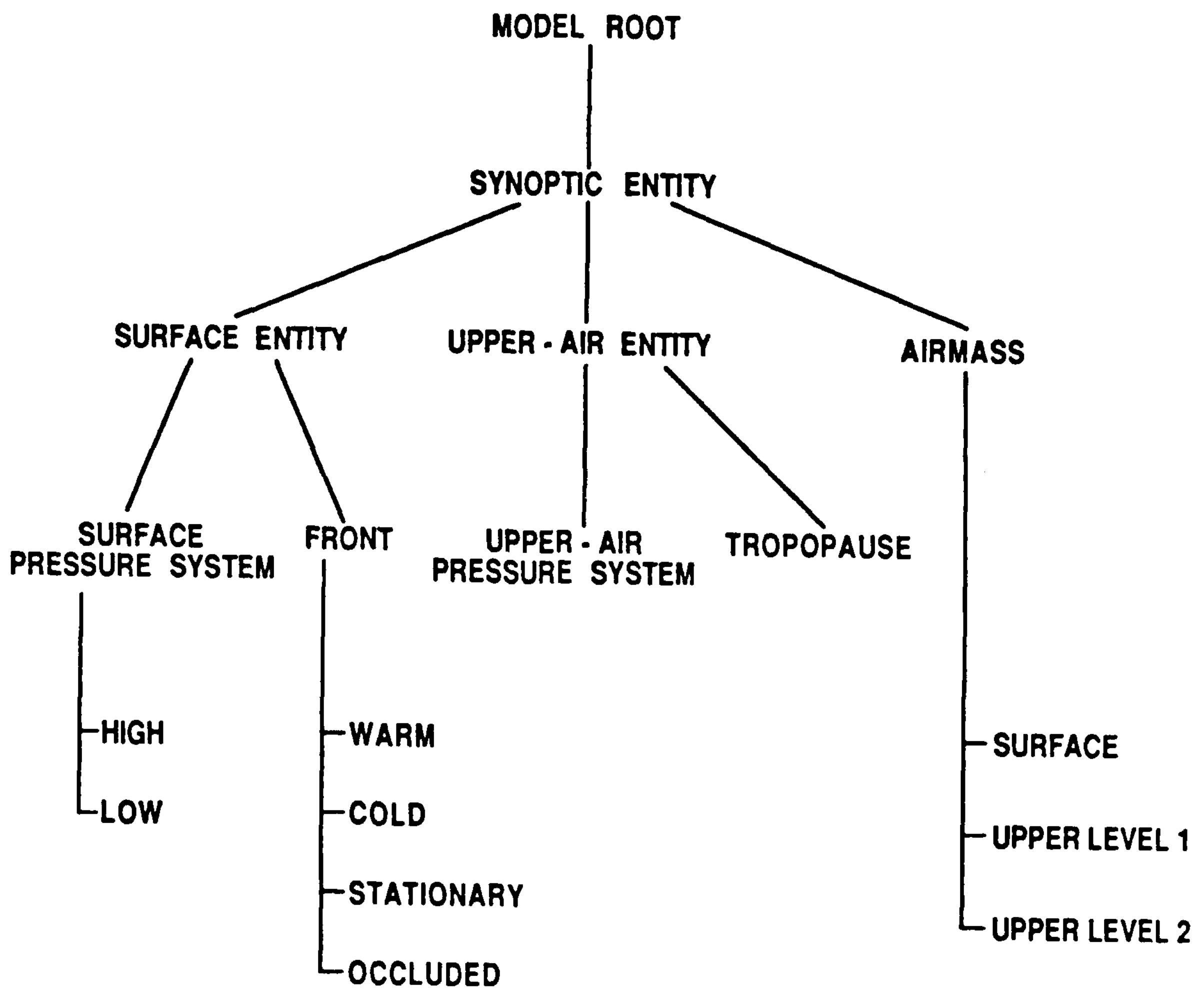
Also, separating the forecasting process into a model-building and a forecasting section allows the users to include their own input at the appropriate place in the forecasting process. That is, they may modify the model, and then the forecast will be based on that best-estimate model.

3.1 Diagnosis

The diagnosis of the specific synoptic model is accomplished through a standard rule-based paradigm which constructs the synoptic model out of meteorological components or entities available to and represented within the expert system. The expert system organizes these components as shown in Fig 2. At the uppermost level is the model root. Currently there is only one branch from the root, and this is to the synoptic entity component. There are three components that branch from the synoptic entity: the surface entity, of which there are surface pressure systems and fronts; the upper air entity, of which there are upper level pressure systems and the tropopause (neither of which are currently active); and the airmasses. This structure provides a physical hierarchy of entities which allows information to be passed between levels.

This representation of the meteorological model allows for the creation of "instances" of the meteorological features shown in Fig 2. For example, when a high is needed by the expert system, it is created with a unique name (e.g. high-2) and with a structure that specifies characteristics of that feature. The system allows any number of instances of high pressure systems to exist simultaneously, and each is an independent entity. The same is true for the fronts and the

Fig. 2: SYNOPTIC MODEL STRUCTURE



airmasses. Upper air entities have not yet been specifically defined in the expert system beyond what is shown in Fig 2.

The expert system creates instances of the synoptic entities as they are required and attempts to infer information about them. The instances of the surface pressure systems, fronts and airmasses have properties as given in Fig. 3. In particular, for surface high and low pressure systems, the expert system attempts to infer the directional location with respect to the station, the distance, the intensity, and the speed and direction of movement. For fronts, inferences are made about the directional location, the distance from the station, the direction and speed of movement, the geographical orientation, and the expected time of frontal passage. The type as well as the pressure at the base and top are inferred for surface and upper-level airmasses. Some of these data may be inferred at the time of the first observation, some may not be inferred until many observations have been made, and some may be inferred only when the necessary information becomes available. The data may also be changed as evidence is accumulated.

The operation of the expert system diagnostic phase can best be illustrated by briefly describing a typical sequence of events. After an observation is entered, the system will attempt to infer information from the observation data, from algorithms contained within the expert system and operation on the observation data or from questions asked directly of the user.

At a given time step, the synoptic model description may be only partially developed. This is particularly true if no upper-air data are yet available. If the observation is not the first one, then a forecast exists from the previous time step and is compared with the new observation. Any significant differences between the data and the forecast will result in possible changes to the model.

At every time step, the current observation and a textual description of the current synoptic model are presented to the user who has the option of accepting or modifying that model. If they choose to modify the model, a series of menus will appear. By responding to the menu questions the model will be changed and presented again to the user.

3.2 Forecasting

A forecast is initiated after the diagnostic phase of the problem, including any modifications made by the user, has been completed. When the forecast process is initiated, the synoptic model is moved forward in time by hourly increments. That is, a copy of the synoptic model will exist for each hour in the forecast period. Each hour's representation will contain updated positions and other information known to the

Fig. 3: PROPERTIES ASSOCIATED WITH EACH METEOROLOGICAL ENTITY

SURFACE PRESSURE SYSTEMS	FRONTS	AIRMASSES
LOCATION (DIR)	LOCATION (DIR)	TYPE
DISTANCE	DIR. OF MOVEMENT	LOWER LEVEL
INTENSITY	DISTANCE	UPPER LEVEL
DIR. OF MOVEMENT	ORIENTATION	
SPEED	SPEED	
	TIME OF ARRIVAL	

model. For example, if the current model assumes that there is a warm front 35 nautical miles south of the station moving northward at 8 knots and that the surface airmass is a modified polar airmass being overrun by a maritime tropical airmass, then the fourth hour would have the front 3 nautical miles to the south and the fifth hour would have the front 5 nautical miles to the north with a surface airmass change to maritime tropical. (Other parameters such as temperature and wind would change according to the rules relating their characteristics to the proximity of the front.)

A forecast is made by applying rules from the forecasting knowledge base to the synoptic model and the past observation(s). A forecast of the weather elements for a given time must be internally consistent. Since changes of each variable from one time period to another do not occur independently, an expert forecaster approaches a final forecast in almost an iterative manner in which the feedback mechanisms and the order of the forecast variable are important. For example, the temperature change from one hour to another is not only dependent upon the time of day, but it is also dependent upon the amount, height and thickness of the clouds, the strength of the temperature advection, the wind speed, and other parameters. Furthermore, the advection is dependent upon the wind speed and the wind speed is dependent on the depth of surface mixing which is dependent upon the surface temperature and the thermal structure in the lower atmosphere. Similarly, convective clouds are dependent upon the low level moisture, the mixing depth and the temperature. The expert forecaster has a reservoir of experience that can be used to bring the forecast to closure without any obvious looping in the process. The weather forecasting expert system has tried to simulate this process in two ways. First, variables are forecast such that the variables that are most independent are forecast before variables that are less independent. For example, wind direction is forecast before clouds and temperature. Secondly, variables that might use a future temperature in its determination can use functions that have been written to give a first approximation of the value to be forecast later. For example, if convection is the expected source of cloudiness, the surface temperature must be predicted before the cloud height, amount or type can be predicted. Since the expert system forecasts temperature after cloudiness, a first approximation of the temperature at a future hour is estimated and used in the cloud forecast. Although this technique appears to work reasonably well, this is an area that will need more development as more sophisticated or complex parameters are used in the forecasting process.

After the first hour, the forecasts are made by applying the forecasting rules to the proper copy of the forecast synoptic model and the past forecast(s) and observation(s). In other words, time only enters into the forecast process with respect

to such things as "hours before frontal passage" or "time of day." Time does not enter into the problem in the form of "this is a three-hour forecast, therefore . . .". The same set of forecast rules are used for all forecasts, and any of the rules in the set can be used, depending on the variables and their values.

Currently, hourly forecasts are made for the subsequent six hours in the manner shown in Fig. 1. When the next observation becomes available, it is compared to the one-hour forecast in order to verify that all forecast variables are within an acceptable deviation. If the deviation is greater than a predefined limit, the observation is high-lighted so that the user's attention is drawn to it. The user may wish to modify the model for the subsequent forecast period.

3.3 AN EXAMPLE

This section describes the highlights of two hours of the expert system operation. The first observation in this example is 0500 LST so that the addition of sounding data taken at 0600 is illustrated.

The expert system uses a window environment supported by ES. The computer screen is divided into four windows: The upper window is the command window which is used to ask the user questions or for the user to respond to questions; the left-center window is used to display the current hour's observation; the right-center window is used to display the forecasts for 1, 3 and 6 hours from the current time; and the lower window is used to present the synoptic description.

When the expert system is started at hour 0500, the observation appears in the observation window. The addition of new observations sets the first overall goal of the system, which is to provide the user with a description of the synoptic situation. This goal activates the diagnostic rules that are needed to build the synoptic model and generate its description. Since the system at this point has only the one surface observation, the resulting synoptic description may be expected to be quite general. Fig. 4 shows the 0500 observation and the resulting description of the inferred synoptic model. The high pressure system is judged to be moderate or strong since it is past the station and the pressure is moderately high. The orientation of the high and low pressure systems is determined from the wind direction after the wind direction is determined to be strong enough in level topography to represent the pressure field. The surface airmass is determined to be return flow from the southerly wind direction and the fact that the dew point is too low for the airmass to be tropical. The location of the warm and cold fronts are climatological in the sense that this is what one would expect with this distribution of pressure systems and with this airmass.

Fig. 4: THE 0500 LST OBSERVATION AND SYNOPTIC DESCRIPTION

Command

Do you want to change the model? (?/y/n) >

Parameter		Current Ob	1 Hour Fcst	3 Hour Fcst	6 Hour Fcst
Time (LST)	(hrs)	500			
Temperature	(F)	47			
Dew Point	(F)	43			
Wind D/S/G	(kts)	180 @ 6			
Pressure	(mb)	1021.			
Visibility	(mi)	12			
Clds	(cov/typ/h)	2 ci 250			

Weather:
Remarks:

Current Synoptic Model

There is a MODERATE-OR-STRONG high pressure system to the SE and a low pressure system to the NW. The surface airmass is RETURN-FLOW-CP. There is a warm front to the S moving N. There is a cold front to the NW moving SE.

With the presentation of the synoptic description, the user is asked in the command window whether or not they would like to change it. If they do, menus will appear allowing any of the characteristics or values of the pressure systems, fronts and airmasses that are present to be changed. If the user chooses not to change anything, the system advances to the forecast portion of its operation and generates six hourly forecasts. The forecasts for the 1, 3 and 6 hour times are presented in the forecast window as shown in Fig. 5. Since this is a relatively benign weather situation and the synoptic model is uncertain, most of the variables show a diurnal variation. The forecast temperature is modified by sky cover, airmass type and other pertinent variables. The surface pressure is forecast to decrease since the high should be moving away from the station. Visibility forecast as 7+ throughout the period indicates that no obstructions such as fog or precipitation are expected. If fog or weather were to be forecast, it would be displayed on the "weather" line. With no information other than this observation, the cirrus is maintained and some cumulus are forecast at the 1100 time at a height determined from the surface moisture and temperature values.

The next observation is requested with a "yes" answer to the question in the command window. At the 0600 observation time, the system also recognizes that an upper air sounding is available. The user is requested to supply the answers to three questions: How many airmasses are evident in the sounding, what are the pressure levels of their boundaries and what types are the upper-level airmasses? With the appropriate answers to these questions and with the 0600 surface and upper air observations, the expert system provides a more complete synoptic description as is shown in Fig 6. In particular, the system determines that the airmass boundary present in the sounding represents a warm front, that the warm front is on the order of 70 nautical miles to the south with an orientation of 120 degrees and that it is moving north at 7 knots. Again at this point the user can change the model if desired or request the forecast. The most significant change in the 0600 hour forecast is that the cumulus clouds present in the prior forecast are replaced by some middle-level altocumulus clouds. The reasoning chain that has been used by the system is that the temperature will not reach the convective temperature of 85 degrees F during the forecast period, thereby eliminating the possibility of surface convective cumulus. In addition, the system adds the clouds at 9000 feet because it recognizes characteristics (dewpoint depressions and stabilities) in the sounding that are indicative of middle-level convective cloud formation.

It is in this way that the system is stepped through each new hour's observation. The synoptic model representation, itself, will update certain parts of the model automatically as each new observation is input. For example, the position of the warm front will be updated each hour without the use of

Fig. 5: THE 0500 FORECASTS

Command

Do you want another ob? (?/y/n) >

Parameter		Current Ob	1 Hour Fcst	3 Hour Fcst	6 Hour Fcst
Time (LST)	(hrs)	500	600	800	1100
Temperature	(F)	47	46	52	63
Dew Point	(F)	43	43	43	43
Wind D/S/G	(kts)	180 @ 6	180 @ 6	180 @ 9	180 @ 12
Pressure	(mb)	1021.	1020.7	1020.1	1019.2
Visibility	(mi)	12	7+	7+	7+
Clds	(cov/typ/h)	2 ci 250	2 ci 250	2 ci 250	1 cu 43 2 ci 250
Weather:					
Remarks:					

Current Synoptic Model

There is a MODERATE-OR-STRONG high pressure system to the SE and a low pressure system to the NW. The surface airmass is RETURN-FLOW-CP. There is a warm front to the S moving N. There is a cold front to the NW moving SE.

Fig. 6: THE 0600 LST OBSERVATIONS, SYNOPTIC DESCRIPTION AND FORECASTS

Command

Do you want another ob? (?/y/n) >

Parameter		Current Ob	1 Hour Fcst	3 Hour Fcst	6 Hour Fcst
Time (LST)	(hrs)	600	700	900	1200
Temperature	(F)	46	48	58	65
Dew Point	(F)	43	43	43	43
Wind D/S/G	(kts)	170 @ 6	170 @ 8	170 @ 10	170 @ 14
Pressure	(mb)	1021.5	1021.2	1020.6	1019.7
Visibility	(mi)	8	7+	7+	7+
Clds	(cov/typ/h)	2 cl 250	2 cl 250	2 cl 250	2 ac 90 2 cl 250
Weather:					
Remarks:					

Current Synoptic Model

There is a MODERATE-OR-STRONG high pressure system to the SE and a low pressure system to the NW. The surface airmass is RETURN-FLOW-CP. There is a warm front 72 miles to the S, orientation 120, moving N at 7 knots. There is a cold front to the NW moving SE.

rules since its distance and speed are known. This representation will be discussed further in the next section.

The reader may have noticed in Figs 4-6 that the range of possible responses to its questions contain a "?" in addition to a "y" and an "n". The "?" response allows the user to explore the reasoning of the expert system in a number of ways, ranging from text descriptions of the knowledge contained in rules that have been used to tables displaying values and goals that have been changed. When the "?" is chosen, the expert system displays a menu which allows the user to choose from among the many options available. The user can return to the expert system and resume its operation when his or her questions have been satisfied.

4. KNOWLEDGE REPRESENTATION

In the course of preparing a short-term weather forecast, the expert forecaster uses conceptual models of the current and forecast synoptic situations, applies intuitive and physical rules to determine the nature of elements in and derived from these models, and uses past data to aid in his/her tasks. As described above, the weather forecasting expert system is designed to operate in a way that resembles the expert's methodology. The knowledge representation used to implement the expert system has been chosen to facilitate this resemblance and has lead to the use of rules (both forward and backward chaining), frames, and lisp functions.

4.1 Rules

Rules are the most straightforward way in which the expert's knowledge is expressed, and generally take the form of *if-then* statements with multiple arguments in each clause. Argum... may be simple truth tests, lisp function evaluations, assignments, or more complex statements that, for example serve to set new goals. Both forward and backward chainin rules are used.

In the weather forecasting expert system, rules are primarily used to express relationships that have some basis in physical laws. Rules are not used to express purely mathematical relationships, such as the Clausius-Clapeyron equation, because such rules would embody no expertise. Experts may use mathematical tools in the forecasting process, but their expertise lies in knowing why and when to use specific tools. For example, while it is known that the intensity and duration of solar radiation can be physically related to the magnitude of the surface temperature change, the relationship is complicated by many other factors such as the soil type and dryness, the surface cover, the thermal structure in the atmosphere near the surface, the wind speed, etc. In practice, an experienced forecaster keys the forecast to the

primary factor or factors in a rather intuitive way, rather than attempting to account for every factor in a mathematically rigorous process. The forecaster normally has a good idea of what the temperature change should be in some average sense and can modify this value in light of other factors. Similarly, the expert system described in this report uses an average mid-latitude diurnal temperature curve and then estimates a multiplicative amplification factor to adjust the normal hourly change on the basis of other parameters.

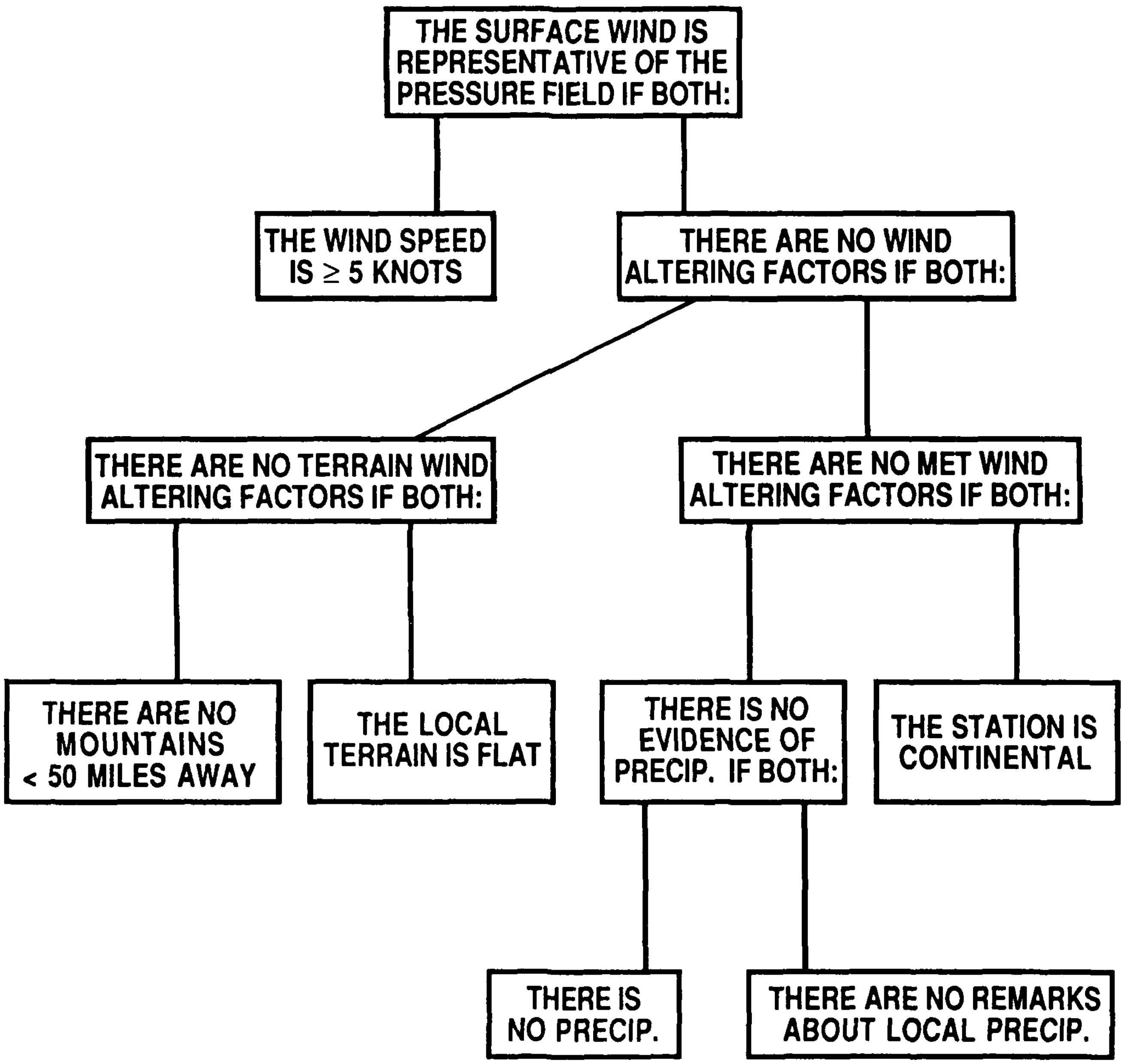
As an example, rule t2 is as follows:

```
1.(b-rule t2
2.  (translate
     "An airmass-class of modified or tropical with "
     "scattered sky cover gives an "
     "average temperature amplification factor.")
3.   (if   (le (sky-cover) 3)
           (= ?am-class 'mod-or-trop))
4.   (then (conclude ?temp-amp 1.0)))
```

where the line numbers have been added to aid understanding. Line 1 identifies the rule as backward chaining and names it. Line 2 supplies the text used to explain the rule, and lines 3-4 contain the meteorological knowledge. The <u>if</u> clause, line 3, asks if it is true that both the sky cover (determined by evaluating the function sky-cover) is less than or equal to 3 tenths and the airmass class is modified or maritime tropical. The <u>then</u> clause, line 4, concludes that the diurnal temperature variation amplitude will be 1.0 times the normal amplitude.

The rules expressing heuristical physical relationships or mechanisms can be categorized by the goal they are meant to satisfy. In general, there are rule groups for each of the variables to be forecast: temperature, dewpoint, wind speed/direction/gusts, pressure, visibility, cloud type/amount/height, and weather. Rule groups also exist for determination of elements in the synoptic model: airmasses, fronts, and pressure systems. There are also rules that determine intermediate results which are used by other rule groups, such as those for pressure tendency, temperature anomaly and representativeness of the surface wind. An example of how a set of rules is used to determine whether or not the surface wind is representative of the surface pressure field is shown in the decision tree presented in Fig. 7. This figure is an example of backward chaining rules which are used whenever a determination of the representativeness of the surface wind is required. The goal in this example is to determine if the surface wind is representative of the

Fig. 7: TYPICAL DECISION TREE



pressure field. Each fact or premise is true if all of the statements immediately below it are true. For example, in Fig. 7, there are no meteorological wind altering factors if there is no evidence of local precipitation and the station is continental. If any of the branches of this tree return a "false", the surface wind is deemed unrepresentative of the pressure field.

The ability of rules to set and satisfy goals allows them to incorporate another aspect of the expert's knowledge: The order in which the various aspects of the analysis and forecast are determined. This is particularly useful in the forecasting process, as described in the previous section, where the order in which variables are forecast depends partially on the values of variables forecast earlier.

4.2 Frames

Frames provide flexible structures which serve to organize data into sets and relate these sets to one another. A simple frame contains a set of named slots, each of which can hold a single value. The frame can be thought of as an object where the slots contain all of the information associated with the object that the frame represents. For example, a surface observation may be thought of as an object with each parameter occupying a slot as described below under section i. More complex frames may have slots that have multiple values, default values or even instructions for computing values. Slots that have these instructions assigned to them are said to contain "procedural attachments" or "demons" which become active when values are added, changed or needed. Examples of this capability are also described below. Frames may be defined in terms of other frames, in which case they can inherit the slots and/or values of the parent frames.

In the weather forecasting expert system, frames are used for the storage of data, both observed and forecast, and to represent the synoptic model. A variety of functions for adding, removing, and retrieving data from frames are incorporated in the expert system shell ES.

4.2.1 Surface Data

Surface data are stored in frames with names that uniquely identify them. Each frame describes the data for one hourly observation, with one slot for each of the observed variables. Two of the slots, wind and pressure, have procedural attachments that automatically determine the symbolic wind direction (e.g. ene or sw) from the angular wind direction and remove the diurnal pressure variation. A slot is also added when the wind is input to give the direction towards low pressure.

An example of the surface data frame structure is presented below. The variable (slot) names are mnemonic. The triple of values for wind are the wind direction, speed and gusts. The pair of values for sky are the total sky cover in tenths and the tenths sky cover opaque. The clouds are given in a series of triples representing the sky cover in tenths, the cloud type and the cloud height in hundreds of feet above the surface for each identifiable cloud layer.

```
(ob200929-26
 (type     (value    sa            ))
 (time     (value    200           ))
 (temp     (value    54            ))
 (dewpt    (value    48            ))
 (wind     (if-added wind-sym)
           (value    (160 6 0)
                     s             ))
 (low-dir  (value    w             ))
 (pressure (if-added scale-pres)
           (value    1021.9        ))
 (vis      (value    15            ))
 (sky      (value    (10 6)        ))
 (precip   (value    nil           ))
 (clouds   (value    ((2 ac 100) (8 cs 250))))
 (weather  (value    nil           ))
 (remarks  (value    nil           ))
)
```

4.2.2 Upper Air Data

Upper air data are also stored in frames with names that uniquely identify them. The variables stored are fewer in type but greater in volume, so that the "sounding" and "ua-winds" slots (see example below) have values that are long lists. The values in the "sounding" slot contain quadruples of pressure, height above sea level (meters), temperature (C) and dew point depression. The values in the "ua-winds" slot contain triples of height above the surface (feet), wind direction and wind speed (knots). The values in slot "hodowinds" contain triples of height above sea level, direction of wind shear and magnitude of wind shear (knots). The heights give the center of the layers over which the wind shear was computed and correspond to the first 10000 feet and the 850, the 700 and 500 mb pressure levels. No procedures are used in the upper air frames.

```
(ua18001001-8
 (time       (value 1800))
 (sounding   (value (998 200 10.2 11.8)
                    (990 267 10.8 14.7)
                    (926 819 5.7 12.7)
                    (850 1511 -1.1 6.1)
                    .
                    .
                    .
                    (127 14820 -58. 99.9)
                    (100 16323 -59. 99.9)
                    ))
 (ua-winds   (value (656 260. 4.)
                    (1000 267.6526 6.550848)
                    (2000 278.3481 11.44199)
                    (3000 273.0338 12.49156)
                    .
                    .
                    .
                    (45000 236.1066 67.19118)
                    (46000 237.8959 61.52071)
                    ))
 (hodowinds (value  (6500 290.9786 22.44609)
                    (5000 321.5622 2.380733)
                    (10000 264.7417 23.04011)
                    (18000 202.6592 10.13969)
                    ))
)
```

4.2.3 Forecast Data

Forecast data are stored in frames (see example below) that are similar to those used for storing surface data. The main difference between the forecast and data frame is the multiple- valued slots of the former, which are used to store current observation and the six hours of forecast data. The forecast frame is re-created each hour through the use of the forecasting rules.

```
(forecast-frame
 (type      (value     sa))
 (time      (value     500 600 700 800 900 1000 1100))
 (temp      (value     47 46 48 52 56 60 63))
 (dewpt     (value     43 43 43 43 43 43 43))
 (wind      (if-added  wind-sym))
            (value     (180 6 0) (180 6 0) (180 8 0) (180 9
0)
                       (180 10 0) (180 11 0) (180 12 0)))
 (low-dir   (value     w w w w w w w))
 (pressure  (if-added  scale-pres)
            (value     1021.0 1020.7 1020.4 1020.1 1019.8
                       1019.5 1019.2))
 (vis       (value     12 7+ 7+ 7+ 7+ 7+ 7+))
 (sky       (value     (2 0) (2 0) (2 0) (2 0) (2 0)
                       (2 0) (2 0)))
 (precip    (value     nil nil nil nil nil nil nil))
 (clouds    (value     ((2 ci 250)) ((2 ci 250)) ((2 ci
250))
                       ((2 ci 250)) ((2 ci 250)) ((2 ci
250))
                       ((1 cu 43) (2 ci 250))))
 (weather   (value     nil nil nil nil nil nil nil))
 (remarks   (value     nil nil nil nil nil nil nil))
```

4.2.4 Synoptic Model

The synoptic model that lies at the core of the expert system is represented by a hierarchy of frames. This hierarchy was presented in Fig 2. At the highest level below the "model root" is the frame named "synoptic entity" which has slots that invoke procedures to move the synoptic features or generate a forecast if the current time is changed or instructions are given to make a new forecast. These procedures will act on all subclasses of the synoptic entity that inherit these features.

The direct subclasses of synoptic entity are "surface entity", "upper air entity", and "airmass", all of which are further divided into subclasses. Airmass, front, and surface pressure system frames also have demons which create new instances of these entities on command from the rules in the expert system. These demons force the evaluation of functions that define the slots appropriate to each entity and set in motion the rules that attempt to determine the slot values.

Two examples of synoptic entity frames, describing a low and a warm front, are presented below.

```
(low-1
 (a-kind-of      (value        low))
 (facet-types    (value        (current
                                 (time single)
                                 (location single)
                                 (distance single)
                                 (intensity single)
                                 (dir-mvmnt single)
                                 (speed single)
                               (forecast
                                 (time ordered)
                                 (location ordered)
                                 (distance ordered)
                                 (intensity ordered)
                                 (dir-mvmnt ordered)
                                 (speed ordered))))
 (make-forecast (if-added      forecast-instance))
 (current        (if-added     move-psystem)
                 (time         600)
                 (location     nw)
                 (distance     unk)
                 (intensity    unk)
                 (dir-mvmnt    unk)
                 (speed        unk))
 )
```

```
(warm-front-1
 (a-kind-of      (value         warm-front))
 (facet-types    (value         (current
                                  (time single)
                                  (location single)
                                  (dir-mvmnt single)
                                  (orientation single)
                                  (time-arrival single)
                                  (speed single)
                                  (distance single))
                                (forecast
                                  (time ordered)
                                  (location ordered)
                                  (dir-mvmnt ordered)
                                  (orientation ordered)
                                  (time-arrival ordered)
                                  (speed ordered)
                                  (distance ordered))))
 (make-forecast  (if-added      forecast-instance))
 (current        (if-added      move-front)
                 (if-changed    change-front-arrival
                                change-front-distance
                                change-front-speed)
                 (time          600)
                 (location      s)
                 (dir-mvmnt     n)
                 (orientation   117)
                 (speed         7.35)
                 (time-arrival  9.93)
                 (distance      73.0))
)
```

4.2.5 Forecast Model

The synoptic model frames are also used to hold the forecast synoptic models, once the make-forecast demon has been invoked. This demon adds multiple-value slots in which the forecast locations, distances, etc. will be placed, and evaluates the functions required to determine the forecast values. The frames are otherwise unchanged, as seen in the condensed examples below.

```
(low-1
 (a-kind-of     ...)
 (facet-types   ...)
 (make-forecast ...)
 (current       ...)
 (forecast      (if-added     move-psystem)
                (time         600 700 800 900
                              1000 1100 1200)
                (location     nw  nw  nw  nw  nw  nw  nw)
                (distance     unk unk unk unk unk unk
unk)
                (intensity    unk unk unk unk unk unk
unk)
                (dir-mvmnt    unk unk unk unk unk unk
unk)
                (speed        unk unk unk unk unk unk
unk))
)


(warm-front-1
 (a-kind-of     ...)
 (facet-types   ...)
 (make-forecast ...)
 (current       ...)
 (forecast      (if-added     move-front)
                (if-changed   change-front-arrival
                              change-front-distance
                              change-front-speed)
                (time         600 700 800 900
                              1000 1100 1200)
                (location     s s s s s s s)
                (dir-mvmnt    n n n n n n n)
                (orientation  117 117 117 117 117 117
117)
                (speed        7.35 7.35 7.35 7.35 7.35
                              7.35 7.35)
                (time-arrival 9.93 8.93 7.93 6.93 5.93
                              4.93 3.93)
                (distance     73.0 65.6 58.3 50.9 43.6
                              36.2 28.9))
)
```

4.3 Functions

The weather forecasting expert system relies on a number of lisp functions to provide analytical and procedural support. These functions may be categorized as meteorological, mathematical, data access, display and frame functions. All of the functions are available to be used anywhere within the system. They may be used by other functions or by the rules that may need a result or a computation in either the IF or the THEN part.

4.3.1 Meteorological

Meteorological functions are, as their name suggests, largely analytical functions designed to do many of the computational chores normally performed by the expert. These functions do not contain expert knowledge per se, in that they represent skills which may be possessed by non-experts. However, the formulation of this technical knowledge in terms of rules would be prohibitive because of the burden on computer resources and the greatly increased complexity of the rule set.

Two examples of meteorological functions are presented below. The first returns the temperature lapse rate in degrees per hundred meters between any two specified levels, and the second function returns an estimate of the convective cloud height given the forecast temperature and dewpoint.

```
(de LAPSE-RATE ($n1 $n2)
   (let* (($lev1  (second (ua-thermo-vals $n1)))
          ($lev2  (second (ua-thermo-vals $n2)))
          ($t1    (third  (ua-thermo-vals $n1)))
          ($t2    (third  (ua-thermo-vals $n2)))
          ($dtdz  (* (/ (- $t1 $t2)(- (float $lev2) $lev1))
100.0)))))
```

```
(de CONV-HT ()
   (* 2.25 (- (last-f-t) (last-f-td))))
```

4.3.2 Mathematical

The mathematical functions may be viewed as utilities which serve mainly to keep the rule-based knowledge efficient and free of clutter. They also facilitate the development of the other functions. The first example presented below converts a vector magnitude and direction to components and the second returns a polar vector which is the sum of two input vectors.

```
(de XY-COMP ($v)
  (cond ((null (first $v)) nil)
        (t (list (* (second $v) (sin (rad (float (first
$v)))))
                 (* (second $v) (cos (rad (float (first
$v))))))))))

(de POLAR-ADD ($v1 $v2 &AUX (r1  (first $v1))
                   (th1 (second $v1))
                   (r2  (first $v2))
                   (th2 (second $v2)))
  (let* ((x (+ (* r1 (sin th1)) (* r2 (sin th2))))
       (y (+ (* r1 (cos th1)) (* r2 (cos th2)))))
      (list (sqrt (+ (* x x) (* y y)))
            (atanm y x))))
```

4.3.3 Data Access

Data access functions return values from frames that are used for data storage. As described previously in this report, frames are used to store the surface and upper air data, forecast data and data about the current synoptic description. The following examples illustrate the functions that return the temperature, upper air data, the forecast temperature, and the location of the most recently created warm front. Each function will return the data from the most recent hour or from any other previous time.

```
(de TEMP     (&OPT (n 1) (obslist *obs-list*))
   (first (fget (nth obslist n) 'temp    'value)))

(de UA-THERMO-VALS (&OPT (lev 1) (nob 1))
   (nth (fget (nth *ua-obs-list* nob) 'sounding 'value) lev))

(de LAST-F-T (&OPT ($n ?forecast-hour))
   (fget-nth 'forecast-frame 'temp 'value $n))

(de WARM-FRONT-LOC (&OPT (n 1))
   (fget-first (warm-front n) 'current 'location))
```

4.3.4 Display

The display functions manage all of the screen displays. The example below is the function that displays the input data. The display uses a window environment, and the input data are presented in window 1.

```
(de DISPLAY-INPUT-DATA ()
  (if (= *grand-es-iteration* 1)
      (setq ?tok t ?tdok t ?pok t ?wdok t ?wsok t) )
  (wl 'clear)
  (wl ':pc "Time (LST) (hrs)  " (time-sfc))
  (wl ':pb "Temperature  (F)  ")
  (flagdata ?tok (temp))
  (wl ':pb "Dew Point    (F)  ")
  (flagdata ?tdok (td))
  (wl ':pb "Wind D/S/G (kts)  ")
  (flagdata ?wdok (first (wind)))
  (wl ':prt "@")
  (flagdata ?wsok (second (wind)))
  (wl ':prt " " (cond ((gt (third (wind)) 0.0) (wl ':pc " G"
(third (wind))))
                (t nil)))
  (wl ':pb "Pressure    (mb)  ")
  (flagdata ?pok (p))
  (wl ':pb "Visibility  (mi)  " (visb))
  (wl ':pb "Clds (cov/typ/h)  ")
  (wl ':prt  (cond ((null (first (obs-clouds))) " ")
                (t (display-obs-cloud-layer (first (obs-
clouds))))))
  (wl ':pb "                  ")
  (wl ':prt  (cond ((null (second (obs-clouds))) " ")
                (t (display-obs-cloud-layer (second (obs-
clouds))))))
  (wl ':pb "                  ")
  (wl ':prt  (cond ((null (third (obs-clouds))) " ")
                (t (display-obs-cloud-layer (third (obs-
clouds))))))
  (wl ':pb "Weather: " (weather) )
  (wl ':pb "Remarks: " (remarks) )
)
```

4.3.5 Frame

Frame related functions, some of which are invoked by demons, perform the tasks of *creating*, *moving*, and describing the many kinds of synoptic entities in the synoptic model. These functions are essential to the updating and operation of the synoptic model within the expert system. The following example is the function that causes the pressure systems to update their data at each time change.

```
(de MOVE-PSYSTEM ($frame $slot $arg-list
             &AUX ($i-frame (first $arg-list))
               ($facet   (second $arg-list))
               ($value   (third $arg-list)))
  (if (neq $facet 'time) nil
      (fput $frame $slot 'time $value)
      (let (($loc (fget-last $frame $slot 'location))
          ($dst (fget-last $frame $slot 'distance))
          ($dir (fget-last $frame $slot 'dir-mvmnt))
          ($spd (fget-last $frame $slot 'speed)))
         (if (and (neq $loc 'unk) (neq $dst 'unk)
               (neq $dir 'unk) (neq $spd 'unk))
          (let (($rslt (polar-add (list $dst (rad (dir-to-
angle $loc)))
                             (list $spd (rad (dir-to-angle
$dir))))))
               (setq $loc (angle-to-dir (deg (second $rslt)))
                  $dst (first $rslt))))
         (fput $frame $slot 'location $loc)
         (fput $frame $slot 'distance $dst)
         (fput $frame $slot 'intensity (fget-last $frame $slot
'intensity))
         (fput $frame $slot 'dir-mvmnt $dir)
         (fput $frame $slot 'speed $spd))
)))
```

5. SUMMARY AND RECOMMENDATIONS

The expert system described in this report is being developed to answer basic questions concerning the use of current expert system technology in solving difficult meteorological problems. The particular problem towards which this work has been addressed is that of single-station forecasting, in which short-range forecasts of basic meteorological parameters are made using data from a single location. This is an important problem for which there is available, although diminishing, expertise. The current work has successfully demonstrated that this expertise can be captured, structured, and put to work in a manner very much like the way an expert goes about solving the forecasting problem. The expert system performance using an archived data set highly resembles that of an expert.

The expert system environment allows a wide range of representations for the knowledge base: heuristic knowledge is contained in rules, computational knowledge is contained in functions, data structure is contained in frames, and system control is provided by the expert system shell. This environment is used to advantage by the single-station expert system, allowing it to be easily modified and adapted to experimentation such as altering or expanding either the knowledge base or the synoptic model. It is this same flexibility that makes the system a computer solution to a problem that normally requires the use of human expertise, and will permit the system to achieve greater levels of performance in the future.

Recommendations for future extensions and modifications include:

Synoptic model: The present synoptic model currently represents surface pressure systems, fronts and airmasses. Further development of the expert system will require that upper air features and possibly other entities be represented and incorporated into the model. Furthermore, additional linkages or relationships should be made between some of the entities to permit the full utilization of the frames representation of the model.

Meteorological conditions interpreted and forecast: As noted above, the present system was put together from a four-day case study and is, therefore, limited in the range of events it can interpret or forecast. As the system is developed further to handle more meteorological situations, the rule set for each of the forecast variables will have to be expanded considerably. For example, the knowledge required to forecast visibility is extensive and depends on many factors, such as current weather, surface winds, humidity, the thermal structure of the lower atmosphere, nearby and distant land usage, and pollution sources. Most of these factors are not considered as influencing visibility in the current system. A large rule set is likely to be required to make forecasts of reasonable quality. In fact, it is estimated that the rule set for each variable will have to be increased by at least an order of magnitude to make the system operationally useful.

Geographical coverage: An analogous problem is that of geographical coverage. The system presently contains rules that are designed for mid-continent locations, and it has no knowledge concerning oceanic, coastal, tropical and polar meteorology. It is intended that this system be built to accommodate different topographic or geographic features and not be station specific. This will require forethought with respect to both the model structure and the rule base.

User interface: The user interface is one of the most important parts of any computer system. A feature of expert

systems is that they have the ability explaining their inferencing to the user, so that the user may have greater confidence in the system forecast or modify a system conclusion that he or she finds to be questionable. While this is generally straightforward in simple systems, the nature of the forecasting problem makes it a complex task. In the course of producing six hourly forecasts, the system currently may exercise a thousand rules or more. How does the user look back through a record of these rules to find the needed information without inconvenience and confusion? At the present time, the system allows the user to modify only the synoptic model. Once the forecast process is initiated the user has no control over it, and may only accept the results as they appear. Queries about the reasoning used during forecasting are complicated for the reason given above. A desirable solution may be one that "bundles" the rules by the conclusion they are working towards without seriously degrading the efficiency of the system. The quality and timing of user interaction with the system is a concern which must be addressed during future development.

A second user interface aspect is that of the presentation, itself. Currently, the "forecast" consists of forecasts of the observed variables. Effort should be made during development to present the forecast in a manner and in a terminology useful to the user. This may include the output of forecast text, diagrams, precipitations probabilities or other specific products.

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